Experimental and numerical study of Sharp’s shadow zone hypothesis on sand ripple wavelength

Erez Schmerler a, Itzhak Katra a, Jasper F. Kok b, Haim Tsoar a, Hezi Yizhaq c,d,*

a The Department of Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva 84105, Israel
b Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095, USA
c Swiss Institute for Dryland Environmental and Energy Research, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, 84990, Israel
d The Dead Sea and Arava Science Center, Tamar Regional Council, Israel

ABSTRACT

Despite advances in understanding processes of sand transport by saltation and reptation, which are involved in the formation of sand ripples, the mechanisms that determine the linear dependence of ripple spacing on wind speed and their relative importance are yet unknown. In a pivotal study, Sharp (1963) proposed that this linear dependence arises from the scaling of the ripples’ shadow zone – the part of the ripple devoid of particle impacts – with the wind speed. Here, we test this hypothesis by integrating wind tunnel experiments with numerical simulations of saltation. Specifically, we measured the effective shadow zone by using sand traps designed for this purpose and found a linear relationship between the shadow zone and the wind shear velocity, consistent with Sharp’s hypothesis. However, contrary to what Sharp assumed, we found that the shadow zone is not completely screened from particle impacts, which as indicated by numerical simulations is due to the wide distribution of impact angles. Nonetheless, the shadow zone can be one of the major mechanisms contributing to the linear increase of the ripple wavelength with wind speed at the nonlinear growth stage of the ripples where merging events between small ripples take place. However, for the initial stage of ripple development, when the ripple dimension is small, other mechanisms can be dominant, such as the recently suggested resonant saltation trajectory (Durán et al., 2014).

© 2016 Published by Elsevier B.V.

1. Introduction

Sand ripples are the smallest aeolian bedform (<30 cm) created in sand, characterized by an asymmetric ridge perpendicular to the prevailing wind direction, usually transverse stable (Yizhaq et al., 2012), and with a unimodal sand size distribution (Fig. 1). The ripple height \((H)\) is defined as the vertical distance between the bottom of the trough to the top of the ridge, and the ripple wavelength \((\lambda)\) is the distance between one ridge crest to the next. The ripple index \((RI)\) is the ratio between \(\lambda\) and \(H\) \((RI = \lambda/H)\) (Bagnold, 1941; Sharp, 1963).

As the wind speed exceeds a certain threshold, sand grains begin to move, mostly through saltation and reptation (Kok et al., 2012) to create ripples. The motion of grains transported by saltation is composed of a series of asymmetric ballistic trajectories which are accelerated by the wind and upon hitting the bed they eject low energy grains. These grains move in small jumps close to the surface through a mode of transport known as reptation (Anderson, 1987; Durán et al., 2014; Warren, 2014).

The ripple dimensions (height and wavelength) grow in time until reaching an equilibrium where the growing ceases and the ripples only drift downwind with a velocity (celerity) which is linearly depended on wind speed (Andreotti et al., 2006; Rasmussen et al., 2015). Their steady state dimension depends on the wind velocity and on grain diameter (Bagnold, 1941; Sharp, 1963; Seppälä and Lindé, 1978; Anderson, 1987; Andreotti et al., 2006; Durán et al., 2014) as shown in Fig. 2.

The basic symmetry-breaking mechanism behind the formation of normal sand ripples is commonly described as a screening instability (Andreotti et al., 2006). When the high energy saltation grains collide with the bed, they eject grains of smaller energy, termed reptons. The windward slope of a small bump is subject to more impacts than the lee slope, so that the flux of reptation particles is higher uphill than downhill, thereby enlarging the bump. Although normal ripples were extensively studied and their
from bombardment by saltation particles.

100 years of research since the work of Cornish (1914) states the ripple wavelength is still in debate after more than these two factors and that ripples start as small bumps that grow in time, their final wavelength not directly related to the mean saltation path. Bagnold’s theory was first challenged by Sharp (1963) who argued that the ripple wavelength depends on the ripple height and on the impact angle \( \alpha \) – at which the saltation grains approach the surface. Thus, the ripple wavelength is mainly dictated by the size of a shadow zone \( s \) (Fig. 3) that is sheltered from a significant sand grain impact. Since the impact angle is inversely related to the wind velocity, stronger winds will produce longer wavelengths since the shadow zone length becomes larger (Cooke and Warren, 1973). According to Sharp (1963), the length of the impact zone \( i \) decreases with wind velocity and increases with grain size and ripple height (see also Pye and Tsoar, 2009). The ripple wavelength can be approximated by \( \lambda = i + s \); thus, if \( \lambda \) increases with wind velocity, the increase in \( s \) should exceed the decrease in \( i \). Thus, the ratio \( i/s \) which is a measure of the ripple asymmetry should increase with grain size and decrease with wind velocity.

According to numerical simulations and wind tunnel experiments, most of the saltating grains impact the surface at angles between 10° and 15° (Anderson, 1987; Nalpanis et al., 1993). Most experiments found that the impact angle decreases with shear velocity \( u_\tau \), and increases with grain size (Jensen and Sørensen, 1986; Willetts and Rice, 1989; Rice et al., 1995; Fu et al., 2013), due to the larger vertical component of the terminal velocity of the coarse grains (it scales as the square root of the grain diameter).

However, in wind tunnel experiments Fu et al. (2013) found a much wider distribution of incident angles (0–180°) than most accepted ranges reported in previous works, probably due to the experimental difficulty to discern between saltation and reptation particles.

Sharp (1963) found a relation between \( \lambda \) and shear velocity \( u_\tau \), but not with the mean grain diameter (Walker, 1981). A linear relation between \( \lambda \) and \( h \) was obtained for steady state equilibrium wind tunnel ripples (Andreotti et al., 2006). Recently it was suggested by direct numerical simulations of grains (45,000) interacting with a wind flow (Durán et al., 2014) that the instability is driven by resonant grain trajectories with a distance that is close to the initial ripple wavelength. The initial wavelength increased linearly with the wind velocity, but the relation to the final wavelength was not clear in this study. Durán et al. (2014) argued that the screening instability predicts a wavelength which is independent of the shear velocity, and that spatial modulation of the saltating flux, which was assumed uniform in Anderson’s model (1987), is needed to explain their new hypothesis.

It is important to note that according to the gravity waves theory for ripple formation, ripples are initiated by Helmholtz instability between the dense saltation layer and the air above it, treating them as two fluids (Brugmans, 1983; Milana, 2009). The prediction of this theory is that the wavelength scales the square of the wind speed, which contradicts wind tunnel experiments and field observations (see Fig. 2).

Uncertainties remain in characterizing the physical mechanisms that control the relations between wind velocities and ripple wavelength and height. We suggest that Sharp’s shadow zone theory can be one of the mechanisms contributing to the linear dependence between the ripple wavelength and wind velocity. This mechanism was explored directly for the first time in this study, by combining experiments in a boundary-layer wind tunnel and numerical models of saltation.
2. Materials and methods

2.1. Experimental set up

Quartz sand collected from the Sekher sands sampling site in the northwestern Negev dune fields (Israel) was used for the laboratory wind tunnel experiments (see details in Roskin et al., 2014). The sand was collected from the upper 10 cm of the sand dunes. Common sizes of the active (loose) sand grains in the Sekher site are in the range of 100–400 μm with modes of 150–200 μm (Fig. S1), which is typical of dune saltators (Bagnold, 1941; Kok et al., 2012).

In order to explore the role of particle size in ripple formation, the sand was segregated into different size fractions due to technical limitation of the requirements to sieve a specific size in natural sands. Three narrow size fractions were obtained using mechanical sieving: 142–200, 200–247, 247–300 μm. These fractions constituted 33.6%, 23.6%, and 12.4% of the Sekher sand, respectively. The grain size analysis of the prepared sand samples used for the experiments is presented in Table 1. Since the sand grains are naturally aspherical grains, the mechanical sieving is limited and some overlapping between the size fractions was expected.

Overall, the results show clear differences in the distribution parameters between the sand fractions (Table 1), which were sufficient for purpose of the experiment. In order to examine ripple formation under large (non-typical) grain sizes, a coarse sand (from a sand mine) was also prepared for the experiment (Table 1).

The grain size distribution of the sand samples was analyzed by a high-resolution laser diffractometer (ANALYSETTE 22 MicroTec Plus) over the range of 0.08–2000 μm. The samples were dispersed in a Na-hexametaphosphate solution (at 0.5%) and by sonication (at 38 kHz), and then transferred to a fluid module of the instrument containing deionized water. The data were processed using the Mie scattering model (Refraction Index = 1.56, Absorption Coefficient = 0.1). MasControl software was employed to statistically determine the mean size, median and modes in multiple modal distributions, sorting values, and size fraction weights.

The aeolian experiments were conducted at the stationary boundary layer wind tunnel of the Aeolian Simulation Laboratory in Ben-Gurion University (BGU) described in Pye and Tsoar (2009) and Katra et al. (2014). The BGU wind-tunnel is an open circuit tunnel with three parts: an entrance cone, a test section, and a diffuser (Fig. 3a). A sand feeder is located close to the entrance cone to allow enough sand supply during the experiments to ensure steady-state saltation. Air is sucked in through the bell-shaped entrance by a fan located at the end of the diffuser. The cross-sectional area is 0.7 × 0.7 m and the working length is 7 m for measurements in the test section. Various instruments are installed in the test section to measure wind and sand variables (see below), and are controlled by a computer during the experiments (Fig. 3).

Table 1

<table>
<thead>
<tr>
<th>142–200 μm</th>
<th>200–247 μm</th>
<th>247–300 μm</th>
<th>500–1000 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>178.2</td>
<td>236.7</td>
<td>285.7</td>
</tr>
<tr>
<td>Mode</td>
<td>176.0</td>
<td>227.0</td>
<td>277.2</td>
</tr>
<tr>
<td>D10</td>
<td>98.25</td>
<td>147.2</td>
<td>158.1</td>
</tr>
<tr>
<td>D50</td>
<td>183.9</td>
<td>240.9</td>
<td>261.6</td>
</tr>
<tr>
<td>D90</td>
<td>258.9</td>
<td>341.5</td>
<td>404.1</td>
</tr>
</tbody>
</table>

Fig. 3. The boundary-layer wind tunnel at Ben-Gurion University. (a) The laser module, 3D camera, and Nikon D-90 installed in the tunnel roof for documentation of ripple morphology. The test section of the tunnel is shown (cross sectional area 0.7 × 0.7 m and the working length 7 m). (b) Instruments are installed in the test section to measure wind and sand transport (vertical traps are at heights of 1, 3, 4.5, and 6.5 cm above the bed surface). The Sensit which appears in the figure was not used in this study. (c) The array of horizontal sand traps used to calculate the effective shadow zone ds.
(the expected fluid threshold) and up to 12 m/s (measured at 15 cm height), strong enough to maintain saltation of particles of size >900 μm in the wind tunnel (Katwa et al., 2014). The initial condition for each experiment with a certain wind velocity was a flat bed. In order to control the stream intensity in the tunnel, for each test (different size fractions) the fan was operated at specific frequencies (Hz): 12.5, 15, 17.5, 20, and 22.5. In each test, the wind speed profile was measured by a micro-vane probes kimo vt200 (www.kimo.com) at the following heights (cm) from the tunnel bed: 2, 3.5, 5, 7.5, 10, 15, 20, 25, 30, 35, 40, and 45. This enabled the calculation of shear velocities ($u_*$) in m/s and aerodynamic roughness ($z_0$) for each fan frequency and sand fraction (see the results section).

In order to maintain a continuous sand flux as occurs in the field, the tunnel was fed during the experiments with sand corresponding to the specific size to be tested. The rate of the sand supply (g m⁻² s⁻¹) was determined based on preliminary measurements at each wind speed performed before the ripple experiment. After ripple development, the operation of the wind tunnel was continued under the same conditions for each experiment. Measurements of wind (described above) and sand (see below) variables were taken in the test section of the tunnel while the ripples were drifting downwind. Three sets of measurements under the same conditions (wind speed and grain size) were obtained in each experiment, which were processed into average values. The transported sand was collected during the experiment by using a vertical array of sand traps oriented in the along-wind direction. The traps, which had a cross section of 2 × 1 cm, were placed at heights of 1, 3, 4.5, and 6.5 cm above the tunnel bed (Fig. 3b). The sand in each trap was weighted after each run to calculate the saltation flux (g m⁻² s⁻¹).

In order to retrieve the shadow zone, an array of horizontal traps was placed in the test section (Fig. 3c). The array is comprised of 10 traps (a cross section of 10 × 1 cm for each). An obstacle with a height of 2 cm above the sand bed was installed at the windward side of the array. The obstacle simulated a ripple element while the transported sand accumulated downwind to create a ripple slope. Thus the array allows the measurements of saltation flux at uniform distances from the obstacle with an interval of 1 cm. The sand in the tunnel bed was flattened before the experiment with the horizontal traps, because these traps have already a barrier in front of them to simulate the ripple height. The wind tunnel was operated under the specific condition of the experiment (wind speed and grain size) for 1 min. Due to the new method applied in this study, 10 sets of measurements (replicas) were obtained of each experiment, and processed into average values. The sand in each trap was weighted after each run to obtain the distribution of the grain distances. The effective shadow zone $d_e$ was defined as the distance where the captured mass is 50% of the maximum mass captured in the traps. In this domain the number of impinging particles is less than 50% of the maximum and the impact angle is quite high so that their efficiency to eject other particles to move in repletion is small (Willett and Rice, 1989). This definition of the shadow zone can be justified as we show in the results section; the shadow zone is not completely protected from saltation bombardment as assumed in mathematical models of ripples formation (e.g., Hoyle and Woods, 1997; Prigozhin, 1999). The main reason for this is the scattering and stochasticity of the impact angle of the saltation particles. Note that this definition is different from the conventional shadow zone definition(s) shown in Fig. 1b, which assume that this area is completely protected from saltation particles. As shown in Section 3.2, this assumption is incorrect and $d_e < s$.

2.3. Ripple morphology

After measurements of the wind and the sand flux, while the tunnel bed was covered with ripples – and before the flattening of the bed for shadow zone measurements (see above) – the ripple morphology was measured, including ripple height and wavelength. A system of a laser module and a Nikon D90 SLR camera, were used to derive the data (Fig. 3a). The module includes a line laser with a diode in the wavelength of 660 nm in ruggedized housing of 19 mm diameter (www.laser-components.com). A high-speed camera (C4-4090-Gige) with sensor resolution of 4096 x 3072 pixels (www.AutomationTechnology.de) was used in parallel to the laser module.

The laser beam was inclined to the tunnel bed (length of 60 cm) and pictures were taken from above the tunnel bed (Fig. 3a). The profile $h(x, y)$ was detected by a correlation method with a precision of 500 μm. Data were obtained by using CX-Explorer software that converts an image file into profile values (Fig. 3c). In the specific setup of the laser module in the tunnel, each profile was comprised of more than 3 ripples (ridges). Since the ripple pattern is usually quasiperiodic (Andreotti et al., 2006), the ripples were characterized by an average wavelength $\lambda$ and average amplitude $A$. Six profiles were measured under each experimental condition (wind speed and grain size). The data produced by the CX-Explorer were calculated by MATLAB for ripple characteristics. The Nikon D90 was used to document the ripple pattern over time from a fixed position above the test bed.

2.4. Modeling of impact angle by the numerical saltation model COMSALT

In order to interpret and extend the experimental measurements of the shadow zone, we used simulations of steady-state saltation over a flat sand bed with the numerical model COMSALT (Kok and Renno, 2009). This model is in generally good agreement with a wide range of measurements of saltation properties, and has previously been used to study dust aerosol emission due to saltation (Kok et al., 2014), the evolution and flattening of megaripples (Isenberg et al., 2011), and the properties of saltation and ripple formation on Mars (Kok, 2010a,b; Yizhaq et al., 2014). In this study, we used COMSALT to explicitly simulate the trajectories of saltating particles over a flat sand bed. We then obtained the probability distribution of the angle with horizontal plane with which saltating particles impact the soil surface from a large number of randomly selected saltating particle trajectories, and we did so for a range of shear velocities and sand particle sizes. For these simulations, we defined a saltating particle as a particle that has rebounded from the surface at least once (Yizhaq et al., 2014).

3. Results

3.1. Wind tunnel experiments

Table 2 shows the calculated shear velocities $u_*$ in the wind tunnel experiments and the surface roughness $z_0$, both of which increase with wind velocity due to the sand flux (Kok et al., 2012).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>247–300 μm</th>
<th>200–247 μm</th>
<th>142–200 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_*$ (m/s)</td>
<td>$z_0$ (mm)</td>
<td>$u_*$ (m/s)</td>
<td>$z_0$ (mm)</td>
</tr>
<tr>
<td>12.5</td>
<td>0.37</td>
<td>0.21</td>
<td>0.34</td>
</tr>
<tr>
<td>15</td>
<td>0.47</td>
<td>0.39</td>
<td>0.42</td>
</tr>
<tr>
<td>17.5</td>
<td>0.63</td>
<td>0.99</td>
<td>0.59</td>
</tr>
<tr>
<td>20</td>
<td>0.77</td>
<td>1.21</td>
<td>0.72</td>
</tr>
<tr>
<td>22.5</td>
<td>0.98</td>
<td>2.34</td>
<td>0.98</td>
</tr>
</tbody>
</table>
The dependence of the saltation flux on the height above the surface is shown in Fig. S2 for the different size fractions and for the highest shear velocity. The exponential decrease of the flux is in agreement with previous works in a wind tunnel (e.g. Rasmussen et al., 2011) and with numerical simulations (Anderson and Haff, 1988; Werner, 1990). Note that the fluxes are almost the same for all the three sand fractions except for the lower trap, where the flux of the finer fraction is the highest.

Table 3 summarizes the morphometric characteristics of the ripples derived from the laser system (see two profiles in Fig. 4) for the three sand fractions and for the different shear velocities.

The linear growth of wavelength with shear velocity is shown in Fig. 5 in agreement with previous studies in wind tunnels (Walker, 1981; Andreotti et al., 2006). The largest wavelength was obtained for most \( u \) values for the finest grain fraction, in agreement with a recent work done in an Aarhus wind tunnel (Rasmussen et al., 2015), but the overall differences between the wavelengths of the three fractions are quite small. Only for \( u = 0.98 \text{m/s} \) was the largest wavelength obtained for the coarsest fraction (247–300 \( \mu \text{m} \)), as probably for this high shear velocity the coarse particles are less easily dislodged from the crest because the fluid threshold velocity increases with the square root of the grain diameter. According to Bagnold (1941) the fluid threshold velocity is \( u_t = A\sqrt{\sigma g d} \) where \( A = 0.1, g \) is the acceleration due gravity and \( \sigma = (\rho - \rho_a)/\rho \) where \( \rho \) is the grain density and \( \rho_a \) is the air density. The ripple height also grows linearly with the shear velocity (Fig. 6), in agreement with previous studies (Andreotti et al., 2006). As both the wavelength and the height grow linearly with wind velocity, the ripples index range does not change significantly (~25).

### Table 3

Morphometric characteristics of the ripples for different fractions. The numbers in the parentheses are the standard deviation.

<table>
<thead>
<tr>
<th>( u ), (m/s)</th>
<th>Wavelength (mm)</th>
<th>Height (mm)</th>
<th>Ripple index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grain size: 247–300 ( \mu \text{m} )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.37</td>
<td>72.45 (15.0)</td>
<td>3.01 (0.39)</td>
<td>24.29 (2.40)</td>
</tr>
<tr>
<td>0.47</td>
<td>74.62 (3.88)</td>
<td>2.85 (0.24)</td>
<td>26.35 (1.71)</td>
</tr>
<tr>
<td>0.63</td>
<td>105.23 (6.49)</td>
<td>4.12 (0.30)</td>
<td>25.66 (2.08)</td>
</tr>
<tr>
<td>0.77</td>
<td>166.04 (15.77)</td>
<td>5.92 (0.37)</td>
<td>28.13 (3.26)</td>
</tr>
<tr>
<td>0.98</td>
<td>248.14 (31.02)</td>
<td>8.14 (1.70)</td>
<td>31.79 (7.87)</td>
</tr>
<tr>
<td><strong>Grain size: 200–247 ( \mu \text{m} )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.34</td>
<td>74.69 (5.70)</td>
<td>2.80 (0.43)</td>
<td>27.01 (2.02)</td>
</tr>
<tr>
<td>0.42</td>
<td>78.43 (4.16)</td>
<td>2.88 (0.35)</td>
<td>27.63 (3.34)</td>
</tr>
<tr>
<td>0.59</td>
<td>101.12 (9.20)</td>
<td>3.88 (0.39)</td>
<td>26.20 (2.57)</td>
</tr>
<tr>
<td>0.72</td>
<td>139.54 (9.84)</td>
<td>5.97 (0.30)</td>
<td>23.37 (1.23)</td>
</tr>
<tr>
<td>0.98</td>
<td>200.87 (9.80)</td>
<td>8.24 (0.58)</td>
<td>24.53 (2.37)</td>
</tr>
<tr>
<td><strong>Grain size: 142–200 ( \mu \text{m} )</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.32</td>
<td>80.73 (5.76)</td>
<td>3.00 (0.31)</td>
<td>27.19 (3.27)</td>
</tr>
<tr>
<td>0.47</td>
<td>95.83 (5.14)</td>
<td>4.24 (0.30)</td>
<td>22.71 (1.78)</td>
</tr>
<tr>
<td>0.63</td>
<td>112.84 (7.59)</td>
<td>6.18 (0.67)</td>
<td>18.39 (1.28)</td>
</tr>
<tr>
<td>0.75</td>
<td>151.82 (7.79)</td>
<td>7.36 (0.67)</td>
<td>20.74 (1.61)</td>
</tr>
<tr>
<td>0.93</td>
<td>217.65 (24.45)</td>
<td>8.83 (1.11)</td>
<td>24.79 (2.42)</td>
</tr>
</tbody>
</table>

Fig. 4. Fully developed ripples \( (D_{50} = 250 \mu \text{m}) \) for \( u = 0.63 \text{m/s} \) and for \( u = 0.77 \text{m/s} \), with the corresponding cross section obtained from the laser scanner (in mm). Note that for the stronger wind the average spacing and height between the ripples are larger.
Fig. 5. Ripples morphology as a function of shear velocity for three fractions as a function of wavelength (a) and as a function of height (b). The linear growth of the wavelength with shear velocity is shown, in agreement with previous wind tunnel studies (Walker, 1981; Zheng, 2009). The largest wavelength was obtained for the fine grain fraction, but the difference between the fractions is quite small and statistically not significant. The ripple height also increases linearly with shear velocity.

Fig. 6. The normalized sand mass distribution in the horizontal traps according to their distance from the barrier for the finer fraction (142–200 μm). The inset shows the absolute mass distribution in the traps. The stronger the wind higher the mass caught in the traps.

Fig. 7. The normalized mass distribution in the traps for the highest shear velocity for three size fractions; the dashed line shows the location of 50% of the maximum mass, which here defines the effective shadow. There is more than 1 cm difference between the coarsest fraction and the finer two fractions. The inset shows the same for the lower shear velocities and the line of 50% of the mass crosses at the same point.

Fig. 8. (a) The effective shadow zone $d_s$ for the three size fractions as a function of the shear velocity. For the two finer fractions, there is a clear linear dependence whereas for the coarsest fraction it is less significant. (b) Ripple wavelength versus the effective shadow zone length. The basic trend is that the larger $d_s$, the larger is the wavelength. For the fine fraction the ratio $d_s/\lambda$ can be as large as 17%.
is steeper for the coarser fraction which implies a shorter effective shadow zone ($d_i$).

The maximum value was used for computing the shadow zone length $d_i$ for each shear velocity by using a second order interpolation polynomial fitting for the data points lying between $0 < x < x_{\text{max}}$, where $x_{\text{max}}$ is the distance of the trap with the maximum sand mass from the barrier (Fig. 8a). The results show that the shadow zone increases linearly with the shear velocity especially for the two finer fractions. Fig. 8b shows the length of the shadow zone as a function of the wavelength. The general trend is that the shadow zone increases with ripple wavelength and it can be as large as 45% of the ripple wavelength for the finer fraction (142–200 μm).

The results for the coarse fraction are less statistically significant, especially for the high wind speed. One possible explanation for this is the wider distribution of impact angles for coarse fraction as observed experimentally by Willetts and Rice (1989). The fact that this fraction is poorly sorted whereas the other two fractions are moderately sorted may enhance this effect. For large shear velocities the effect of turbulence on grain trajectories becomes more significant. We further explored the effect of turbulence using COMSALT simulations.

### 3.3. Numerical study of the impact angles

In order to help interpret our experimental results, a numerical simulation of the impact angle for a range of wind speeds and two particle sizes, was performed with the numerical saltation model COMSALT (Kok and Renno, 2009). As shown in Fig. 9, these simulations find a decrease in the mode of the impact angle with $u_i$, which is consistent with both Sharp’s (1963) hypothesis and with the finding from the wind tunnel experiments that the shadow zone increases with $u$. (see Fig. 8). Furthermore, the simulations show that smaller saltating particles impact the sand bed at shallower angles.

### 4. Discussion and conclusions

The method used in this study did not allow direct measurement of the impact angle or of the mean shadow zone due to the wide distribution of impact angles. We also ignored midair collisions between particles, which can modify the regular ballistic trajectory (Durán et al., 2014). The new simple setup of traps used here, allowed measurement of the effective shadow zone defined as the distance where the impact rate is half of the maximum. Using other values around half maximum for defining the effective shadow zone does not change the trend reported previously. Using much higher threshold values is not appropriate, since at this point the shadow zone is not effective. Thus, the arbitrary definition presented in this study does not affect the basic trends presented in the previous sections.

The numerical simulations indicate that the impact angle decreases with the grain diameter, in agreement with previous studies (Jensen and Sörensen, 1986; Rice et al., 1995). This likely explains the lower terminal velocities of the smaller particles (see, e.g., Fig. 22 in Kok et al., 2012), and thus the lower vertical speeds and more horizontal trajectories of these particles. Furthermore, the impact angle decreases with $u_i$, which likely explains the increase in the shadow zone with $u_i$. The mean angle found in the wind tunnel experiments (see Figs. 1 and 8). In turn, the increase in the shadow zone with $u_i$ would produce an increase in wavelength with wind velocity. However, during ripples evolution, both impact and shadow zones (measured as defined in Fig. 1b) increase linearly with shear velocity (Fig. 10), whereas according to Sharp (1963, p.626) the impact zone should decrease with wind velocity due to the inverse dependence on the impact angle, and the increase in the impact energy of the saltating particles will produce a steeper impact slope which means a smaller $i$. Sharp’s argument is probably wrong as the ripple height also increases with wind velocity which means a larger impact zone. Our analysis shows that the ratio $i/s$ decreases with shear velocity as the shadow zone ($s$) grows faster than the impact zone ($i$) (Fig. 10a). For $u_i = 0.72$ m/s this ratio is close to 1.35 for the 200–247 μm fraction, which means that the shadow zone is approximately 42% of the ripple.

**Fig. 9.** COMSALT simulations of the probability distribution of the angle with which saltators impact a flat soil bed, for monodisperse soils with particles of (a) 169 μm and (b) 272 μm, and for different values of $u_i$ that roughly correspond to those in the wind tunnel experiments. (c) The circles denote the mode of the impact angle for 272 μm particles, which decreases with increasing $u_i$ and with decreasing particle size. The squares show the same for 169 μm particles.
wavelength. The increase of $d_s$ with shear velocity also supports Sharp's shadow zone theory, but it is important to note that the view of a complete impact-free shadow zone as used in previous mathematical models for ripples formation (Hoyle and Woods, 1997; Yizhaq et al., 2014) is not accurate. That is, due to the wide probability distribution of impact angles (Fig. 9) and due to midair collisions (Sharp, 1963; Durán et al., 2014) there will always be some impacting particles in the shadow zone.

The approximately linear decrease of the impact angle with wind speed (Fig. 9c) can potentially explain the observed linear relation between wavelength and wind speed (Andreotti et al., 2006; Durán et al., 2014). For faster winds the impact angle will be shallower and the effective shadow zone will be larger, resulting in the formation of bedforms with longer wavelengths (Sharp, 1963; Greeley and Iversen, 1985; Lorenz and Zimbelman, 2014). According to Fig. 1b, we can approximate the ripple wavelength as the sum of the impact and shadow zone, $\lambda = i + s$. As both the impact and the shadow zones linearly increase with wind velocity, it is clear that the wavelength will also grow linearly with wind velocity. The effective shadow zone $d_s$ can be approximated as $d_s = \eta h / \tan \alpha$, where $h$ is the ripple height, $\alpha$ is the mean impact angle and $\eta$ is a parameter that depends on the grain size. Thus, the increase of $d_s$ with shear velocity is a result of both the increase in the ripple height $h$ and the decrease of the mean impact angle $\alpha$. The increase in $h$ is more dominant than the decrease in the mean impact angle, so that the effective impact zone increases almost linearly with shear velocity. The wavelength can be written as $\lambda = i + s$, and $i$ and $s$ increase linearly with wind speed which means scaling $\lambda \sim u_s$.

Our results basically support the Sharp shadow zone hypothesis, although the simple view of the shadow zone which is completely screened form saltating particles is inaccurate. However it is important to note that there are probably other mechanisms that act to increase the wavelength with wind speed, one of which was recently suggested by Durán et al. (2014). According to their model, the modulation of the reptation flux is driven by resonant saltation trajectories, those whose hop length is comparable to the ripples’ wavelength. As these resonant trajectories increase with wind velocity, the wavelength will also have the same dependence on wind velocity. However, their explanation does not take into account the effect of shadow zone which develops when the ripples are high enough to shelter downwind sand from impacting grains.

Andreotti et al. (2006) used laser profiling to measure stages of aeolian ripple formation on a rather fine sand (120 $\mu$m), starting with a flat bed in a wind tunnel (see results in Fig. 2). They identified three stages in ripple evolution: appearance of an initial wavelength, coarsening of the pattern, and finally (typically after 10 min) a saturation of the ripples so that statistically ripples will migrate without changing their morphology. Within this framework, the resonant trajectories mechanism (Durán et al., 2014) is probably more dominant at the initial stage of ripple growth when the ripples are small ($h \approx 25$ times grain diameter in their simulation) while the shadow zone mechanism is more dominant in the later stage where nonlinear interactions between successive ripples increase ripple wavelength and height. It remains for future studies to determine the relative importance of these two mechanisms in ripple formation.

What scales the ripples size? This fundamental question is still not fully answered. Is the spacing of ripples related to the mean reptation length (Anderson, 1987) or to the mean saltation length (Rasmussen et al., 2015)? COMSALT simulations were used to study the correlation between the mean saltation hop length and the mean ripple wavelength as shown in Fig. 11 for $D = 250 \mu$m (Fig. 11). It is clear from these simulations (Fig. 11) that:

1. The mean reptation length does not depend on the shear velocity so it cannot explain the linear increase of the wavelength with wind speed.
2. Bagnold’s theory of the characteristic path length is also problematic as the mean saltation length is substantially larger than the final ripple wavelength, especially for strong winds (see also the discussion in Fenton et al., 2013). The mechanism which
saturates the ripple growth is also not fully understood, although it could be related to the increase of shear stress at the ripple crest due to flow convergence preventing further ripple growth (Bagnold, 1941; Manukyan and Prigogin, 2009). If correct, this still leaves open the questions of why the ripple height also grows linearly with speed and why the larger ripples were obtained with the fine fraction since the finer grains can be entrained more easily from the crest. One possible explanation is that the shear velocity at the surface below the saltation layer decreases with $u$, above the saltation layer to a value below the impact threshold; thus it cannot dislodge grains from the crest despite the fact that the shear velocity is higher above the saltation layer (for more details see Kok et al., 2012). The physical reason for this is that during steady state saltation the mean impact speed of a saltator must remain constant, thus the increase of $u$, in the upper saltation layer implies a decrease of $u$, in the lower saltation layer. We leave the investigation of this hypothesis for future work.

Finally, it was suggested that aeolian ripples are a good example of self organization patterns where ordered spatio-temporal structures spontaneously emerge (Anderson, 1990; Hallet, 1990; Yizhaq, 2008). Self-organization is a process by which patterns at the global level of a system emerge solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system’s components are executed using only local information without reference to the global pattern (Meron, 2015). The implication of this framework for ripple formation is that the final wavelength is not dictated by any external forcing, but is developed only by local interactions between small scale ripples subjected to the turbulent flow of air that at some point inhibits further growth. Thus, it will be impossible to find a simple characteristic length in the system that correlates with the final steady state wavelength selected by the system.

Acknowledgments
This work was supported by the German-Israeli Foundation for Scientific Research and Development (GIF Research grant 1143-60/8/2011) and by the United States-Israel Binational Science Foundation (BSF Research grant 2014178). We thank Prof. Klaus Kroy from Leipzig University for important discussions during the study that provided us a better understanding on the mechanism of ripple formation. We also thank two anonymous reviewers for their helpful comments which significantly improved the manuscript.

Appendix A. Supplementary data
Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aeolia.2016.05.006.

References


